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PREDICTION AND VALIDATION OF TOTAL ENERGY SAVINGS IN A SOLAR THERMAL HYBRID VARIABLE REFRIGERANT FLOW SYSTEM WITH AID OF ANFIS

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ABSTRACT

The primary function of the current research is to incorporate an artificially intelligent software in a variable refrigerant flow (VRF) system which can effectively monitor energy usage and result in energy saving. The energy is regulated with a bunch of parameters which majorly influence load in any VRF setup. Furthermore, the sustainability aspect is maintained in the VRF system as it uses solar energy to regulate the cooling effect. An adaptive neuro-fuzzy interface system (ANFIS) is employed to successfully predict the overall cooling load and energy saving required for approaching the next controller cycle, which is implanted into the control algorithm. The control parameters can be predicted with the aid of AI which depends on the accuracy of various models, thereby choosing the most effective and energy efficient among them. Initially, the predictive control algorithm was embedded with ANFIS model which further evaluated the performance of the cooling system displayed through graphical representation. The results showed that through various models of ANFIS, gaussian model is accurately close the experimental data with lower RSME value (0.017). Application of this predictive control algorithm remarkably lowered the energy consumption rate by approximately 40.12 % compared to a conventional setup. Henceforth integration of a VRF system with ANFIS can yield revolutionary results with higher prediction accuracy and better energy efficiency.

KEYWORDS: Variable Refrigerant Flow (VRF), Solar Energy; Adaptive Neuro-Fuzzy Interface System (ANFIS), Predictive Control Algorithm; Artificial Intelligence

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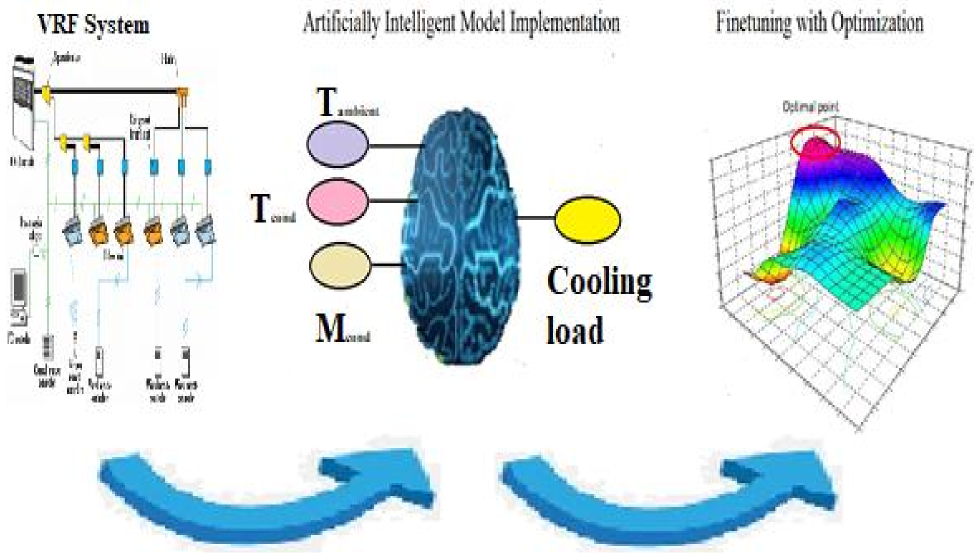
GRAPHICAL ABSTRACT



NOMENCLATURE

1. ANFIS — Artificial neural fuzzy interface system
2. CLF — Cooling load factor
3. CLTD — Cooling load temperature difference
4. MOE — Ministry of energy
5. TOE — Ton of oil equivalent
6. RMSE — Root mean square error
7. ASHRAE — American Society of Heating, Refrigerating, Air-Conditioning Engineers
8. SA — Supply air
9. MFR — Mass flow rate
10. SR — Solar irradiation
11. P-Load — Percentage internal load
12. VRF — Variable refrigerant flow

INTRODUCTION

The ever-growing population which has multiplied several folds over the last two decades has put immense pressure on available earth's resources to fulfil the energy requirements of each and everyone. Due to this surge in energy demand, several countries are looking for alternatives to safeguard and preserve excess energy which can, later on, be used for other humanitarian purposes. Also, exhausting conventional sources of energy have other implications also like environmental degradation, global warming, crude oil resources exhaustion and exhaust gases emission [1,2]. In India, the supply-demand ratio is extremely unbalanced, thereby creating major energy crises across the country. Drastic precautions need to be taken to safeguard this energy loss by diverting our attention to the building department which consumes a substantial part of energy usage approximately 45 % of total energy production across the country [3,4]. Over the years energy consumed by residential and commercial setups have increased several folds possibly due to the economic growth country is witnessing [5,6]. The current research is therefore focussed on predicting an effective framework of reducing the total energy requirement of the building by pre-hand prediction of energy requirement on daily basis, thereby consuming only energy based on the climatic variations which have also been performed in previous researches in past with other frameworks, encountered by the building throughout a year.

Moreover, the cooling apparatus required in the building system requires a substantial portion of building energy to meet the comfortable conditions specified by user [7].In India, the overall losses due to the temperature variations in the building envelope is computed to be around 41 % of the original energy requirements of the buildings. To monitor and control this system a pre-designed framework is required which reduces overall air-conditioning capacity within the room setup based on a certain input parameter. To regulate the above parameters, variable refrigeration flow system is incorporated in a building setup. These VRF system in residential and commercial setups have substantial benefits over the conventional system such as cost effectiveness, load variation adjustment, better efficiency and lower area usage [8,9].

Broadly air-conditioning systems can be classified into two major groups: Water-cooling and air-cooling systems. The VRF system is made from a combination of several outdoor units, a cooling tower and centrifugal pumps as depicted in Fig.1. Previous researches have explored several refrigerants which is evaporated in AHU coil connected to numerous outdoor components. Furthermore, this is coupled to a cooling tower system [10]. The primary reason behind VRF systems being more efficient than a medieval system is that it is regulated by an adjustable speed drive operating superiorly [11].

Despite the considerable benefits prescribed above for VRF system, its employment and potential has not been explored in terms of artificial intelligence prediction and optimization techniques. These techniques if integrated properly result in revolutionary results saving tons of energy yearly [12,13]. Predicting ideal conditions for input parameters will maximize the outputs resulting in a better overall framework [14]. The parameters which majorly influence the VRF cooling system are mass flow rate, solar irradiation and percentage load which are considered the input parameters. These parameters if not set according to energy saving needs will result in substantial losses furnishing improper thermal conditions during the entire year. This is evident as climatic conditions vary throughout the year resulting in lower efficiency [15]. Thereby, a conscious effort should be put in while adjusting values of the VRF input system suggesting optimal values for all parameters. This will eventually result in a better efficient and cost-effective solution.

In order to understand the relationship of various inputs over several outputs, artificial neural network is applied which predicts the cooling building load. This effectively reduces the number of experimental runs, thereby reducing running cost and time. In previous building load related studies various researchers have employed ANN technique to reduce the number of operations with appreciable results [16]. The present research is based on the evaluation of the cooling load and energy saving of a particular building fixture using VRF technology.

The primary goal of this research is to develop a prediction framework which is proficient in predicting output parameters of the VRF system which will depend on a set of input control parameters evaluated by adaptive neuro-fuzzy network system (ANFIS). Basically, in the initial stage, a control algorithm is established and integrated with ANFIS framework to recognize the best optimal input function in ANFIS with the lowest error rate RMSE (root mean square error). The ANFIS algorithm works perfectly in determining the best optimal combinations which leads to maximizing outputs which simultaneously predicting the outputs for future reference. The performance of any ANFIS model in past researches were compared through the RSME error established in each model of ANFIS which also validates its prediction accuracy. Finally, the system predictive values of energy saving were compared with earlier models employing the conventional technique of cooling system.

The novelty of the current research is prevalent since absolutely no previous work has been reported for boosting building performance and reducing power usage while employing prediction models (ANFIS) forVRF based building setup. The application of soft computing techniques coupled with optimization VRF-based monitoring technique will yield revolutionary results in the current field of sustainability.

SYSTEM DESCRIPTION

In order to explain the various connection established in a VRF system a pictorial depiction is provided in fig 1. This comprises of various indoor units integrated with other one major outdoor unit. Some systems preferably do not require a series of ducts to transfer the air cooling. The intelligent technology inbuilt in such a system can be depicted by the indoor units which primarily assume itself to be evaporators when cooling is the prime requirement. In difference, when the

indoor units involve heated air it accepts itself to be a condenser. Moreover, the VRF-based arrangement undergoes a repeated cycle which involves the transference of thermal energy from the specific zone into the affecting refrigerant which additionally moves into the chilling scheme. The current examination has forecast the VRF-AI model to be more lucrative to the arrangement since these structures a VRF scheme which basically is an updated model of the original ductless multi-split apparatus. This eventually enables a substantial number of indoor units to be employed within the system and further being connected to various outdoor units. The primary advantage associated with this arrangement enables lowered costs and simultaneous heating and cooling. The heat regaining organizations are functional to yield both the effects heating and cooling in the calculation to the heat recovery which additionally diminishes the complete energy necessity.

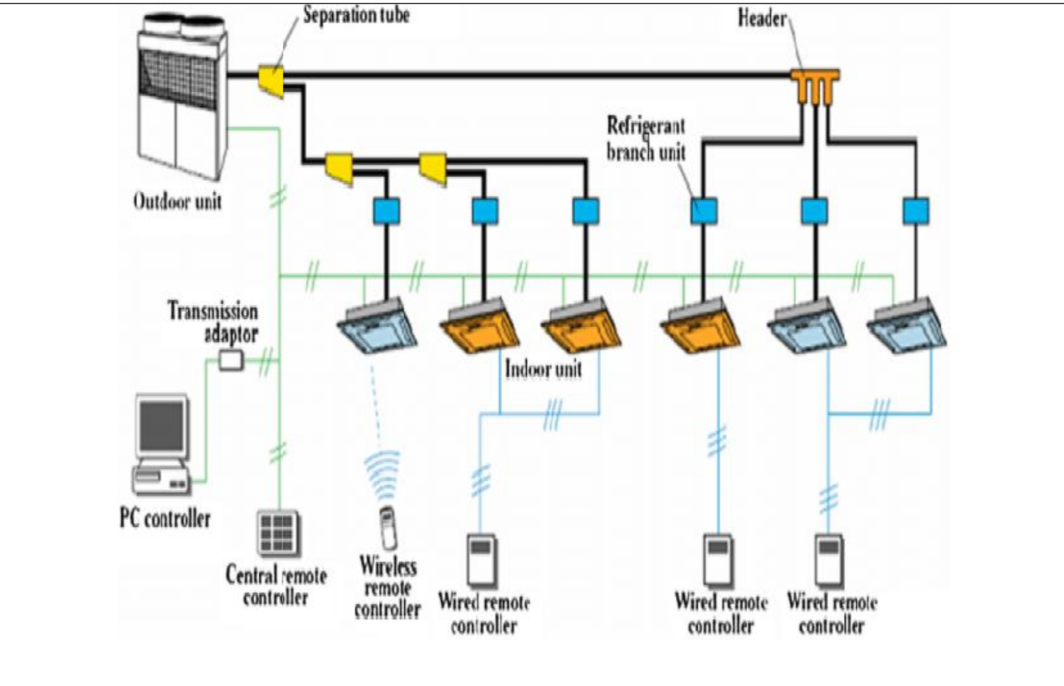


Figure 1: Components of VRF System

VRF arrangement operates motor speediness created on the location of electronic enlargement valve of all internal components. Electronic expansion valve original information drives to PCB over message cable. The controller then provides expertise to compressor to run at compact speed to lower energy usage. Water is heated over solar collector panel of evacuated tube nature. The amount of superheating will be decided based on compressor discharge gas temperature measured through temperature sensor on compressor discharge line. Now, compressor will do partial work and partial work corresponding of refrigerant gas superheating will done by solar operated hot water in chamber. Now, controller gives command to compressor to run further at reduced speed corresponding to superheating achieved in the insulated hot water chamber.

METHODOLOGY

The basic methodology applied in this research was established by making a predictive control algorithm with the aid of software MATLAB. In this, we used the ANFIS from the tool box where input data was established in various models. The flow chart listed below in fig shows the total process of predictive control framework. The solar irradiation, percentage load and mass flow rate were measured at various set points for which the cooling load was estimated and input in the

ANFIS model. The variables collected were considered the input parameters for which different rules were developed at various input combinations.

Preliminary functional procedures such as predefining the input and output variables are performed to maximize the end result. The experiment and analysis were conducted by selecting three inputs: solar irradiation, percentage load and mass flow rate. It is upon this benchmark that the input proposed will be evaluated for best cooling load and energy savings for VRF building structure. Some hybrid approaches have been presented in this paper to compare the experimental and predicted data explained in four successive steps: (i) Accumulation of the acquired experimental data and clustering the data based on training and testing, (ii) Based on the environmental conditions theoretical data generation (iii) Identifying the best performance model in ANFIS data structure for evaluating the performance of VRF building structure, (iii) Comparative analysis among the results of ANFISand theoretical models for among them and (iv) Finally, generalization and validation of the results with previous models.

The framework developed by ANFIS model is presented in fig 2 which takes in all three variables at various optimal points for evaluating the output. For various models of ANFIS the best model was compared on the basis of RMSE value (best being the lowest value). The model with lowest value was selected as the best possible framework and most efficient among others. The whole process took at least 300 minutes and repeated after every 5 minutes and repeated sequentially after every cycle. This framework will provide future researchers a model to compare values of their model to the ideal model and obtain best possible results.

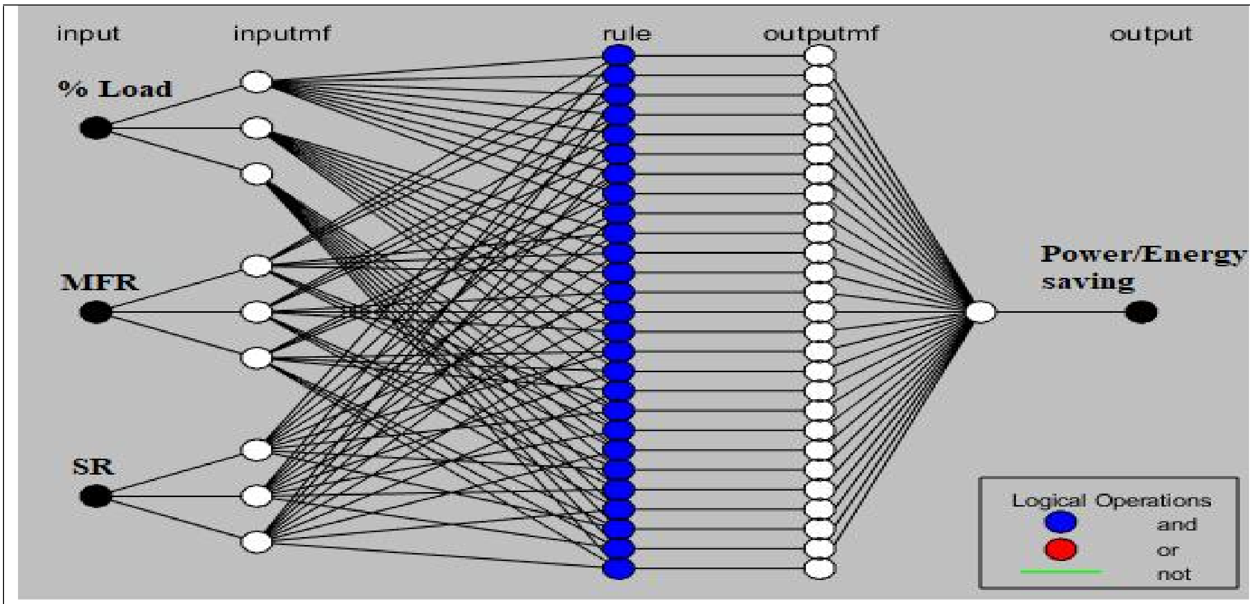


Figure 2: Framework Displaying Inputs and Outputs

Modelling Through Artificial Intelligence

Basic modelling method employed in the study was the first order Takagi-Sugeno artificial neuro-fuzzy interface system (ANFIS). The experiment was structured on the above model as depicted in Fig.3 so as to evaluate the cooling load. Similar models have been earlier established in previous works of literature for modelling various unclear and difficult thermal engineering applications with limited, nonlinear, and uncertain database [17,18]. Recently ANFIS models have gained substantial popularity due to its capability to build effective fuzzy rules, facilitating efficient surface plots between

various input and output responses. Practically, there is an urgent desire to implement such artificial neural techniques in VRF setups since this methodology may prove as a perfect alternative to the conventional experimental techniques, thereby furnishing outcomes with enhanced reliability. General model of ANFIS comprises of six major layers with initial layer of input parameters, followed by fuzzification layer, rule consequent layer, rule strength normalization layer, rule consequent layer, and finally the rule inference layer. Constructing a feasible ANFIS structure indicates the presence of the Fuzzy Theory and membership frameworks which follows the equation 3-12. Approximately 24 sets of input variables and data patterns were generated from the experiments categorizing them randomly into two subsets, i.e., 18 and6 data for the training and testing ANFIS models, respectively. The framework of the single ANFIS model is explained in table 3**.**

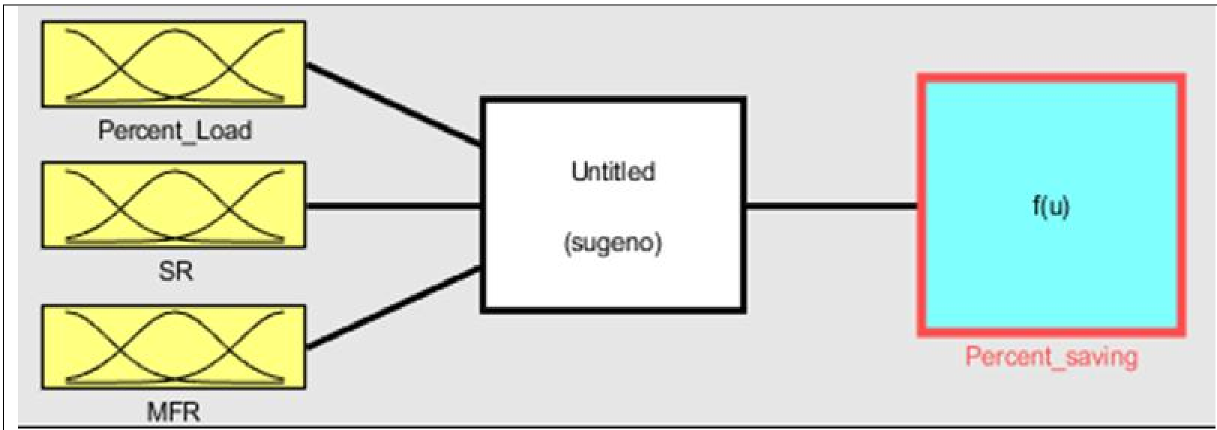


Figure 3: Framework of ANFIS Model

The following equations of ANFIS were applied to generate different responses by modelling

Layer 1- Fuzzification layer:

$$Q_{1,i} = \mu_{A_i}(x)\ ,\ for\ i = 1,2\ \ or; \ldots\ldots(3)$$

$$Q_{1,j} = \mu_{B_j}(y)\ ,\ for\ j = 1,2; \ldots\ldots(4)$$

$$\mu_{A_i}(x) = \frac{1}{1+\left[\left(\frac{x-c_i}{a_i}\right)^2\right]^{b_i}} \ldots\ldots(5)$$

Layer 2- Product Layer:

$$Q_{2,i} = \overline{w_i} = \mu_{A_i}(x)\,\mu_{B_i}(y),\ for\ i = 1,2; \ldots\ldots(6)$$

Layer 3- Normalized Layer:

$$Q_{3,i} = \overline{w_i} = \frac{w_i}{w_1 + w_2},\ for\ i = 1,2 \ldots\ldots(7)$$

Layer 4- Defuzzied Layer:

$$Q_{4,i} = \overline{w_i} f_i = \overline{w_i}\,(p_i x + q_i y + r_i),\ for\ i = 1,2; \ldots\ldots(8)$$

Layer 5- Total Output Layer:

$$Q_{5,i} = overall\ output = \textstyle\sum_i \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \ldots\ldots(9)$$

$$f = \frac{w_1}{w_1 + w_2} f_1 + \frac{w_2}{w_1 + w_2} f_2 \quad (10)$$

$$f = \overline{w_1}(p_1 x + q_1 y + r_1) + \overline{w_2}(p_2 x + q_2 y + r_2) \quad (11)$$

$$f = (\overline{w_1} p_1 x + \overline{w_1} q_1 y + \overline{w_1} r_1) + (\overline{w_2} p_2 x + \overline{w_2} q_2 y + \overline{w_2} r_2) \quad (12)$$

Table 1: ANFIS Framework For Training The Drone-Camera Based Model

Total number of nodes	193
Number of linear parameters	81
Number of non-linear parameters	36
Number of training data pairs	45
Number of rules that are fuzzy	81

Generally, cooling load and energy saving characteristics-based modelling begins with developing a precise objective function which complies with the complexity of the problem statement. Conventional methods employed to generate objective function for several input and output parameters consumes considerable time and labour. However, the ANFIS technique furnishes an acceptable objective function due to its capability to generate the data without the requirement of any previous model history. Estimations and predictions determined from ANFIS technique can be further fine-tuned with improved precision and efficiency by employment of genetic algorithm in output responses a depicted in table 1.

Often it is seen the ANFIS technique may not be 100 % accurate as the outcomes are caught within the local optima. Also, the conflicting outputs complicate the model development. To overcome this complexity, a control algorithm is developed which takes in all the complexities of the environment and are employed to solve complex building related problems quickly and effectively.

All major data applied and generated in the ANFIS models are provided in the table. The discrepancy in the developed model could be explained with statistical tools such as mean-squared error (RMSE) provided in Eqs.13.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - E_i)^2} \quad (13)$$

RMSE = Root Mean Square Error, P_i = Forecast value obtained from modelling, E_i= Experimental value generated, N= Available Data, i= Trial run value need to be calculated.

RESULT AND DISCUSSION

The values were obtained with utmost precision and are based on a set of parameters such as solar irradiation, mass flow rate and percentage load. The process needs to be performed quite quickly due to which the nature of the substances may not be taken into consideration.

Impact of Percentage Load and Solar Irradiation (SR)

3 -D graphs were plotted to understand the combination of two parameters on a certain output. In figure 4 combined effects of solar irradiation and percentage load were seen. It is evident from the graph that with an increase in load the savings increase up to a point at 60 % beyond which it then decreases drastically. A similar pattern was obtained for solar irradiation where an increase in solar irradiation increases percentage saving but then decreases it drastically. Zenith

percentage saving of 70 was obtained when solar irradiation was 750 and percentage load maintained at 60 %. Henceforth, the load should be maintained at 60 % with solar irradiation of 750 W/m^2. Minimum work is achieved at higher solar irradiation and lower percentage load.

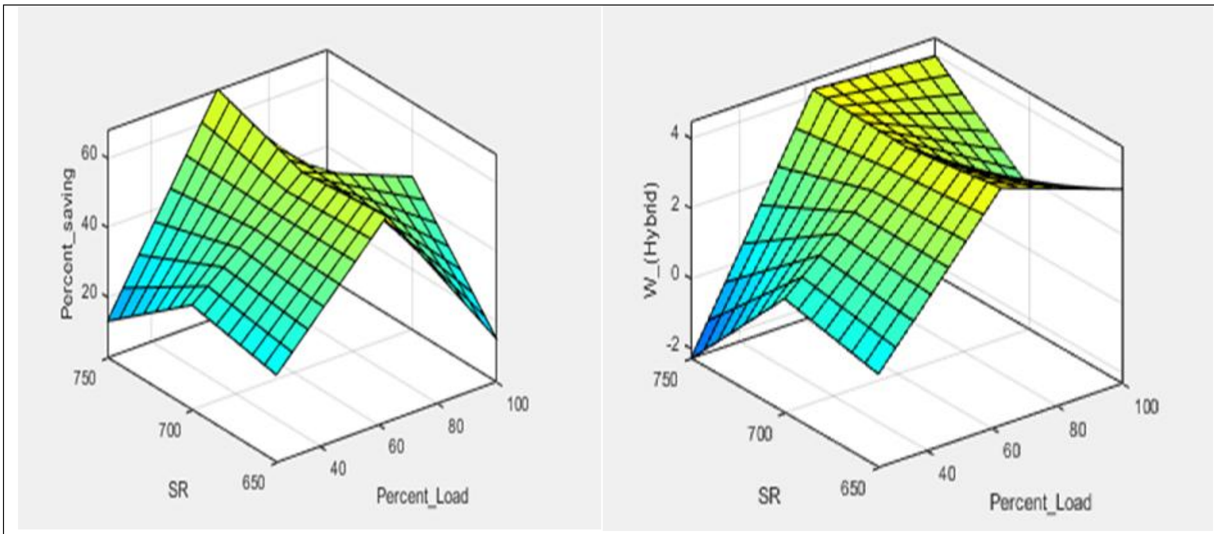


Figure 4: Impact Of Percentage Load And Solar Irradiation (SR)

Impact of Solar Irradiation (SR) and Mass Flow Rate (MFR)

Since in this study inputs more than 3 are considered hence we have to analyse the complete set of constraints for all outputs in figure 5. Here the combined effect of solar irradiation and mass flow rate is to be examined for energy saving and power outputs. With an increment in mass flow rate the energy savings reach at a peak of 53 % at 0.1 mass flow rate beyond which it drastically drops. Also, maximum energy savings were obtained at 0.1 mass flow rate and 750 solar irradiation. For power usage combined effects of solar irradiation and mass flow rate depicts maximum at 650 w/m2 and 0.1 mass flow rate.

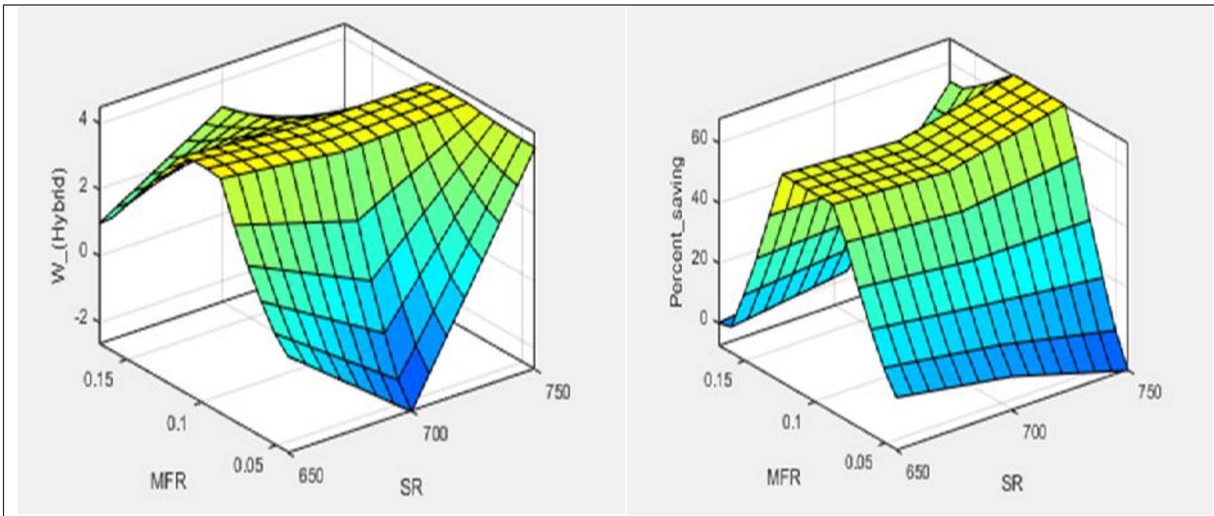


Figure 5: Impact of Solar Irradiation (SR) and Mass Flow Rate (MFR)

Impact of Mass Flow Rate (MFR) and Percentage Load

Lastly, the combination of mass flow rate and percentage load together are considered and depicted in figure 6. here again percentage saving was analysed for combined effects and with increase in mass flow rate the percentage saving declined quickly with maximum savings being achieved at lower mass flow rates. Also increasing load declined the savings. Zenith savings were achieved at a combined effect where mass flow rate was 0.1 and percentage load 60 %. For minimum power usage maximum load to be attained is 60 % whereas mass flow rate has to be maintained at 0.05.

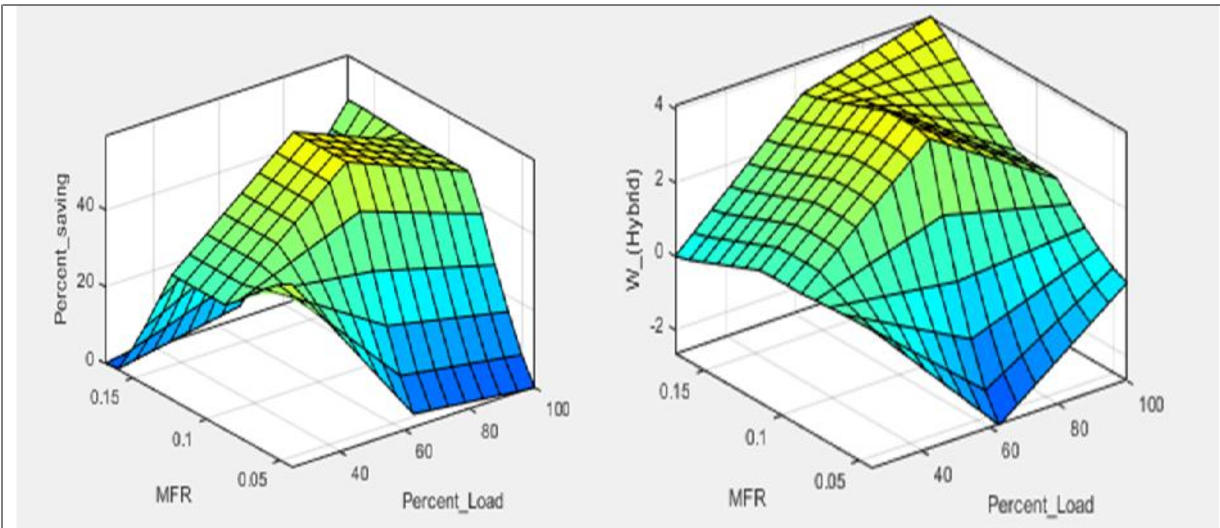


Figure 6: Impact of mass flow rate (MFR) and percentage load

Prediction and Validation of Outputs with Artificial Intelligence (ANFIS)

ANFIS prediction method is applied to analyse a logical correlation for multiple inputs involving total power consumption and energy savings in this study. Experimental results for multiple test runs were achieved under varied climatic factors.

Algorithm-based fusion is carried out to enhance the massive functionality of the structure developed for the testing drone settings. Previous studies have shown the effectiveness of ANFIS architectures consisting of 3 training data inputs and four stages to be applied effectively in well-defined, complicated technical situations. For every response function, the FIS (fuzzy interface system) is individually developed for three ANFIS training input data functions. About 27 rules were created inside the system deemed appropriate network topology when combining the experimental parameters with the required factors. The rules established for both power output and energy savings are represented in figure 7 and figure 8.

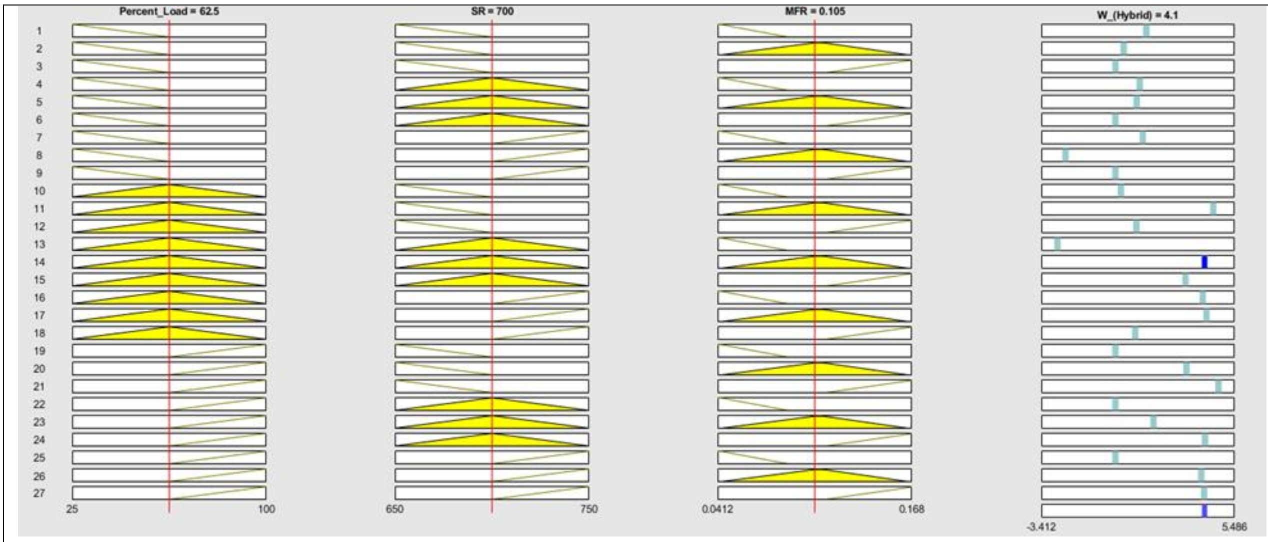


Figure 7: Rules Developed for Power Consumption

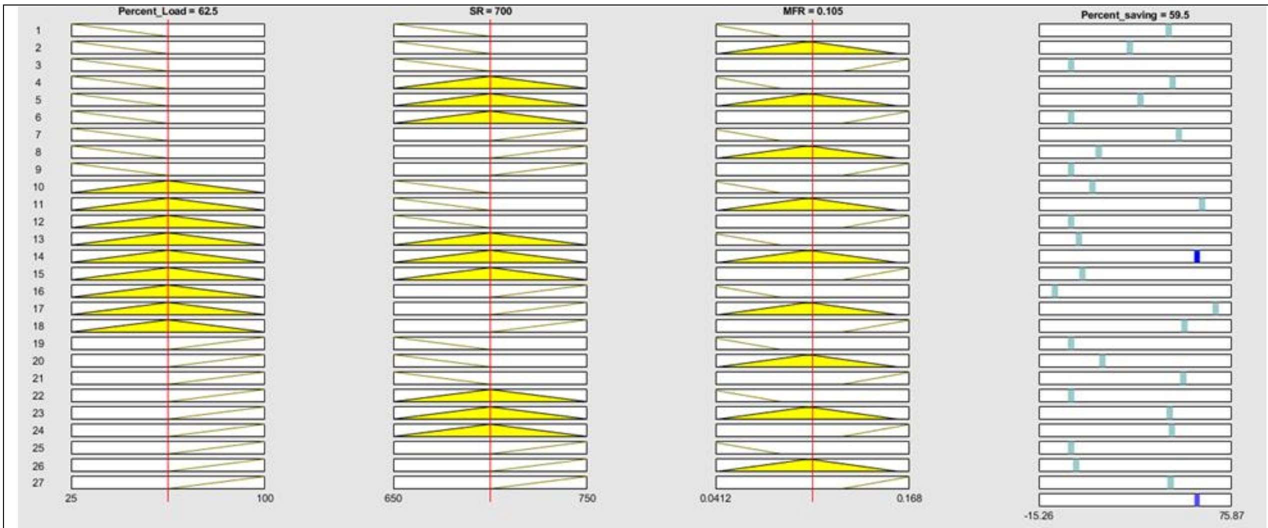


Figure 8: Rules Developed For Percentage Saving

For different types of membership functions, error percentage is achieved so as to contemplate the best working model among them. Minimum error was achieved in the case of triangular function for power whereas triangular membership function attained lowest error rate in energy saving. Also, triangular membership predicted better outputs for energy saving and power output as evident from table 2.

All error percentage for different membership functions are displayed in table 2 with minimum error rates highlighted in yellow. Using the ANFIS method, dependable values have been projected similar to prior theoretical produced data sets used to train and test all response parameters. The forecasted values examined after ANFIS model understand the relationship between each constant shows the validation of the proposed formula as values attained are quite close to those attained in the formula.

The outcomes estimated by hybrid models (ANFIS and conventional) were evaluated on the basis of regression formulas such as root mean square error (RMSE). Often these statistical tools are employed to estimate the deviation between the experimental and predicted responses.

Table 2: Comparative Error Percentage Results of ANFIS Modelling for Various Relationship Functions

Relationship Function	Percentage Saving	Power Consumption
Triangular	**1.73E-03**	**2.97E-04**
Trapezoidal	**0.00937**	**0.00556**
Cubic	**6.99E-03**	**1.53E-03**
Gaussian 1	**5.58E-03**	**1.06E-03**
Gaussian 2	**8.51E-03**	**1.86E-03**
Polynomial	**0.01403**	**0.01069**
Generalized Bell	**8.71E-03**	**2.12E-03**

Impact of Maximum Temperature on Power Consumption

Figure 9 clearly shows that the power consumption increases, the mass flow rate also increases which is responsible for higher energy requirements and thereby lower energy savings. Figure 10 gives mass flow rate, power requirement and COP for different months of the year thereby predicting values in advance of power consumption. This will aid in regulating the overall flow properly based on climatic conditions. Data known prehend will lower energy consumption substantially thereby increasing power usage substantially.

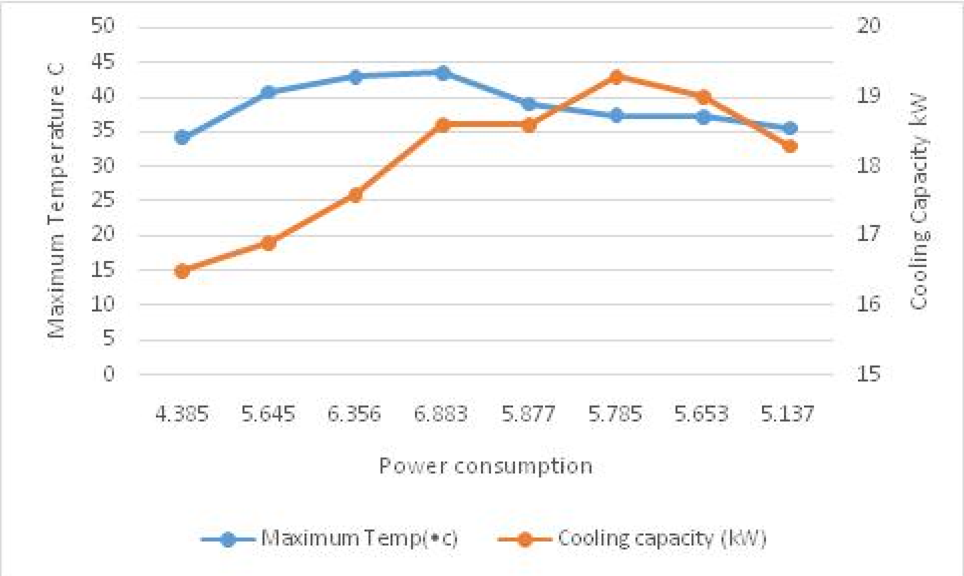


Figure 9 : Impact of Maximum Temperature on Power Consumption

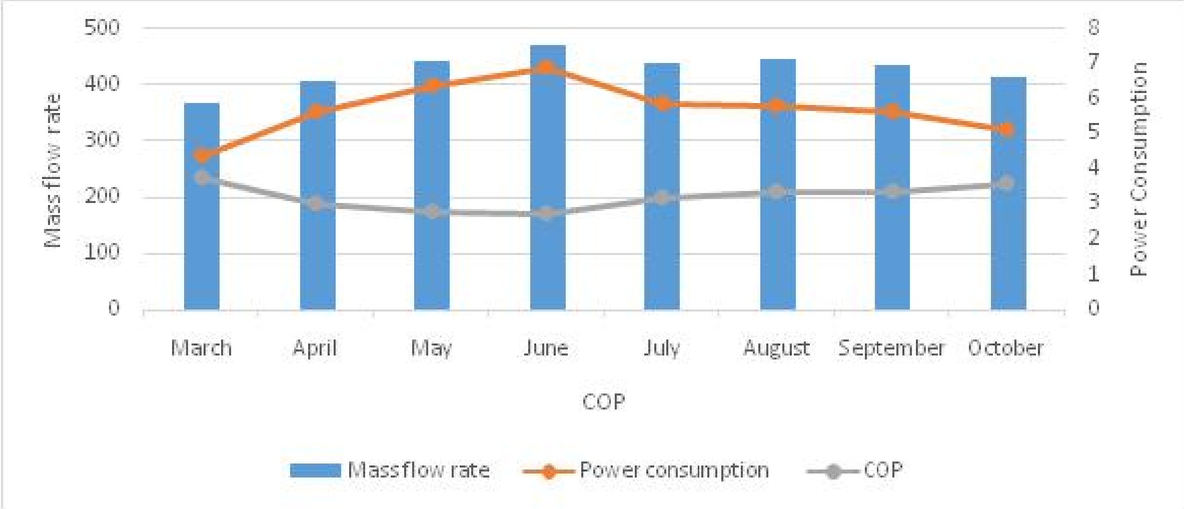


Figure 10 : Variation of Mass Flow Rate, Power Consumption and COP for Various Months

CONCLUSIONS

The current research incorporated a VRF system which worked on a framework developed by ANFIS model which efficiently predicted the cooling load with optimum input variables. The ANFIS algorithm required a set of input values of the variables which developed a set of rules which predicted cooling loads in cost effective and fast manner. The efficiency of the predicted values was compared to conventional models already incorporated in the earlier systems. Within the ANFIS framework, values were also compared each other with models of ANFIS within. The total savings were also predicted by comparing its results with the conventional method. The complete research is coined in the given points below:

- The ANFIS model is integrated in the VRF system which displayed an adequate prediction precision. For 24 runs developed in the RSM model the deviation between actual values and predicted values was 3.2 % which is an acceptable range.
- The range developed for the three input parameters namely percentage load, solar irradiation and mass flow rate of condenser were fairly accurate as most values lied between them, deeming our framework accurate.
- In the ANFIS model, the most accurate model with lowest RMSE value was triangular membership function with an error rate of 0.0017.
- Approximately for 24 test runs the total energy saved by regulating the cooling load through AI is 40.12 % which shows a total saving a cost of Rs 12000/month ($160).

The above points explained in the research, it is resolved that the ANFIS-based prognostic controller algorithm holds a confirmed forecast precision and that it is suitable for operational VRF refrigeration arrangement in relationships with energy-effectiveness.

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